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Transportation Research Procedia 14 (2016) 1305 – 1314

Transportation Research Procedia

www.elsevier.com/locate/procedia

6th Transport Research Arena April 18-21, 2016

How to protect the tunnel SOS niche wall in the event of vehicle impact

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Abstract

An increase in the number of traffic accidents in tunnel emergency stop areas has been recored in the last two years in many countries with long road tunnels. In most cases, the collisions of passenger cars into the emergency stop area walls were fatal, which presents an even bigger obligation for the road management authorities to find a solution to the problem. Even though the tunnel emergency stop areas tunnels are designed and built according to the valid legislation, it has turned out that the current implementation of the emergency stop area wall in the driving direction presents a serious potential traffic safety risk.

With the purpose of determining the most suitable method of protecting the SOS tunnel niche wall in the event of vehicle impacts, comparative numerical analysis of vehicle impacts has been performed in accordance with the SIS – EN 1317 standard. For the emergency-stop-area wall-impact protection, two different designs were considered: the H2 safety railing and the crash cushion composed of eight cylindrical steel sheet tubes. The tube diameter is 500 mm and the sheet thickness is 3 mm. Both designs were subject to collision simulations in accordance with EN 1317 parts 1 and 2 (EN 1317-1 – -4). As the safety of passenger cars was being studied, the tests TB 11 (vehicle mass 900 kg and vehicle velocity 100 km/h) and TB 21 (vehicle mass 1300 kg and vehicle velocity 80 km/h were simulated with a finite-element-model-based explicit dynamic analysis. The kinematic values of the vehicles just prior to the collision were determined by simulating the driving dynamics several seconds before the collision in PC-Crash. Based on the FEM analysis results in LS-Dyna for each crash scenario, a comparative analysis of the two protection systems was performed in order to determine their efficiency and suitability for installation in the existing tunnel emergency stop areas.

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Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)
doi:10.1016/j.trpro.2016.05.203

Based on comparative analyses of the values of the Acceleration Severity Index (ASI), Theoretical Head Impact Velocity (THIV) and values of the Post-Impact Head Deceleration (PHD), the crash cushion provides the best results for the events of impacts of TB 11 vehicles and TB 21 vehicles into an SOS tunnel niche.

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: Tunnel emergency stop area; accident; steel safety railing; crash cushion

1. Introduction

The Slovenian Motorway Company (DARS, d. d.) as the operator of the tunnels on the Slovenian motorway network has since 2009 observed a rising trend of traffic accidents as a result of collisions into the walls of the tunnel SOS niches. Since 2009 to mid-2012 there have been eight collisions into the tunnel niche head walls and they have all resulted in fatalities (Fig. 1). This is a commitment for the operator to take measures of implementing adequate solutions for protection of the problematic SOS niche head walls. Although all the tunnel niches are designed according to legislation (RSV (1987) and Stojanovski (2010)), they have proven as a faulty traffic safety related detail. According to the stated, the requirement is to find a suitable solution for protecting the dangerous spots.

Fig. 1. Tunnel niche wall collision (photo courtesy of Fire brigade Koper).

2. Work method

Two measures for protecting the tunnel niche head wall in the case of a vehicle collision were compared based on finite-element-method analysis, regarding the influence of the collision on vehicle occupants. The first protection measure was the H2-type safety railing; the second measure was the group of VECU-STOP combinable elements. The simulations were performed according to the EN 1317/1 and EN 1317/2 norms for the TB 11 test (a 900 kg passenger car at 100 km/h) and for the TB 21 test (a 1300 kg passenger car at 80 km/h). The vehicle impact angle was determined from a simulation of vehicle dynamics prior to the collision.

The selection of the more suitable protective measure will be made based on the following in-jury criteria: ASI (Acceleration Severity Index), PHD (Post-impact Head Deceleration), THIV (Theoretical Head Impact Velocity).

3. Standard overview

Decree on technical normatives and design conditions for road tunnels in the Republic of Slovenia – SOS-NICHE DIMENSIONS (DARS 2003) prescribes that the SOS-niches have to be implemented instead of the hard shoulder in road medium and long tunnels in the distance of 1000 m from each other, unless the traffic arrangement requires otherwise. Accordingly, the SOS-niches in the tunnels are 40 m long and 2.5 m wide (3.0 m in tunnels with high-speed roads) (Fig. 2). The construction details not specified in the decree are implemented according to the Austrian directives RVS 9.281 and RVS 9.233.

The EN 1317 standard defines the following criteria:

- Acceleration Severity Index (ASI) is ex-pressed with the boundary accelerations that act on the vehicle and consequently on the vehicle occupants upon vehicle collision. The recommendation assumes that the vehicle occupants are using the safety belt. The ASI values are classified into three levels: A, B and C ([A] ASI $\leqslant$ 1.0; [B] 1.0 < ASI $\leqslant$ 1.4; [C] 1.4 < ASI $\leqslant$ 1.9). The acceleration limits that are allowed to occur upon the collision of the vehicle into the obstacle are thereby defined in three directions ($\hat{a}x, \hat{a}y, \hat{a}z$):

$$ASI\left(t\right)=\sqrt{\left(\overline{a}x/\hat{a}x\right)^{2}+\left(\overline{a}y/\hat{a}y\right)^{2}+\left(\overline{a}z/\hat{a}z\right)^{2}} \tag{1}$$

- Theoretical Head Impact Velocity (THIV) is the velocity of the head in the instant of its collision with the vehicle interior. THIV is a measure of severity of the collision of the vehicle into the safety railing. The THIV value is intended for load evaluation and is de-fined as:

$$THIV=\left[v_{x}^{2}\left(T\right)+v_{y}^{2}\left(T\right)\right]^{1/2} \tag{2}$$

- Theoretical Post-impact Head Deceleration (PHD) according to research corresponds to the acceleration of the head during its impact with the vehicle interior due to collision of the vehicle into a safety barrier. The upper limit of the parameter is determined based on the data about the vehicle motion during and after its collision with the obstacle. The upper permissible limit for PHD is 20 g. PHD is expressed as a deceleration relative to earth gravity g with:

$$PHD=MAX\left(\prec \ddot{X}_{C}\succ^{2}+\prec \ddot{Y}\succ^{2}\right)^{1/2} \quad \text{for } t\succ T \tag{3}$$

For the safety railings the EN 1317 standard recommends that the limit value of the ASI of the collision should not exceed 1,0 for the A-level, for the B-level it should be between 1,0 and 1,4 and for the C-level between 1,4 and 1,9. The criterion is fulfilled if the THIV value of the collision is less than 33 km/h and the PHD value is less than 20 g. For the crash cushions the EN 1317 standard recommends that the limit value of the ASI should not exceed the value of 1,0 for the A-level and should be between 1,0 and 1,4 for the B-level. The criterion is fulfilled if the THIV value of the collision is less than 44 km/h and the PHD value is less than 20 g.

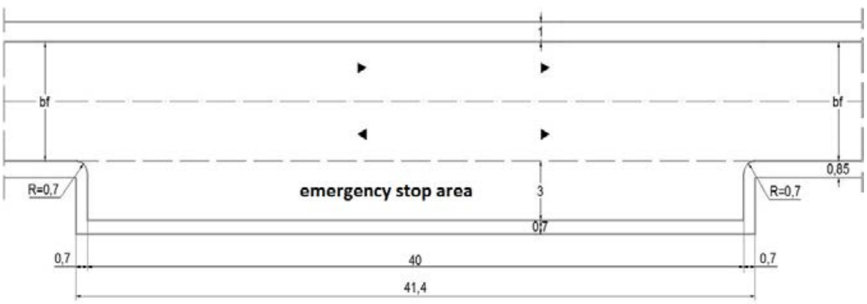


Fig. 2. Top view of the tunnel area with a single sided SOS-niche.

4. Numerical simulation

4.1. Test vehicle models

For simulating the influences of the collisions on the vehicle occupants during the impact into the safety barriers, the following two vehicles have been selected (http://www.ncac.gwu.edu/vml/models.html):

- Suzuki Swift passenger car for the test criterion TB 11 (Fig. 3a),
- Dodge Neon passenger car for the test criterion TB 21 (Fig. 3b).

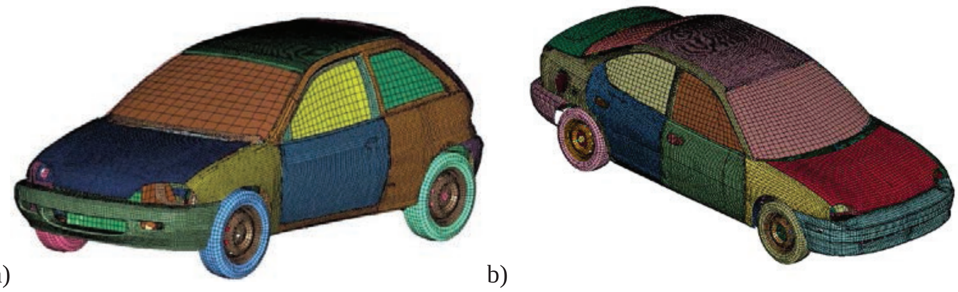

a) b)

Fig. 3 (a) Suzuki Swift passenger car; (b) Dodge Neon passenger car.

4.2. Safety barrier modelling

According to the limitations (most importantly the length of the tunnel niche), which are imposed in order to provide the space for a vehicle combination (HGV with trailer (Fig. 4) and tractor-semitrailer) can entirely retreat into a SOS-niche, a suitable solution for the protection of the dangerous spot has to be found. The solutions are searched for in the frame of the following possibilities:

1. Protection of the tunnel niche head wall by means of a H2-type steel safety railing.
2. Protection of the tunnel niche head wall by means of compound elements of the VECU-STOP crash cushion system.

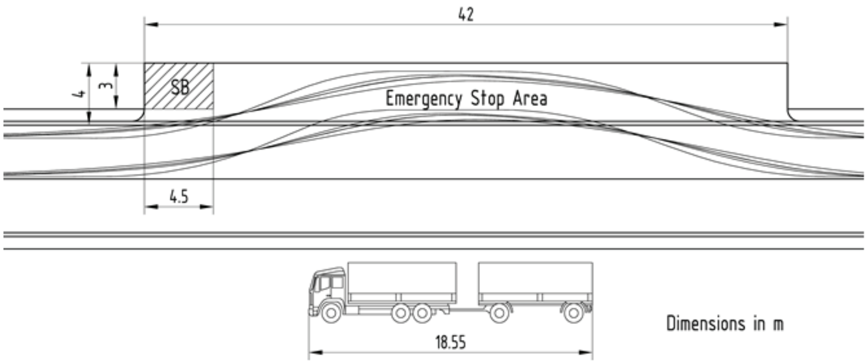
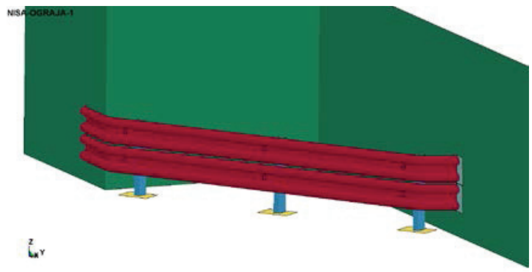


Fig. 4. Emergency stop area in a tunnel niche with vehicle wheel tracks.

The steel safety railing (SSR) geometrical model is based on the H2-type safety railing model manufactured by Petrič, d. o. o., where the horizontal inclination of the railing against the road axis is approximately 17 ° (Fig. 5).

a) 

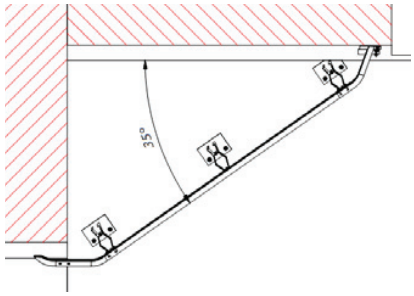
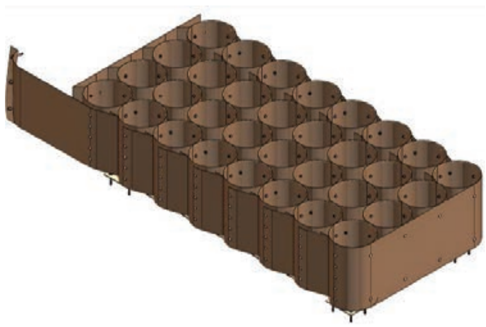
b) 

Fig. 5 (a) SSR geometrical model; (b) Placement of the SSR.

The crash cushion in the tunnel niche is com-posed of four rows of eight Ø500 mm tubes made of 3 mm thick steel sheet (Fig. 6a). Its geometrical model is based on design documentation, reports and brochures of several different types of crash cushions (BASt/2000 and BASt/2004), and adapted to fit into the required length of the tunnel niche (Fig. 6b).

a) 

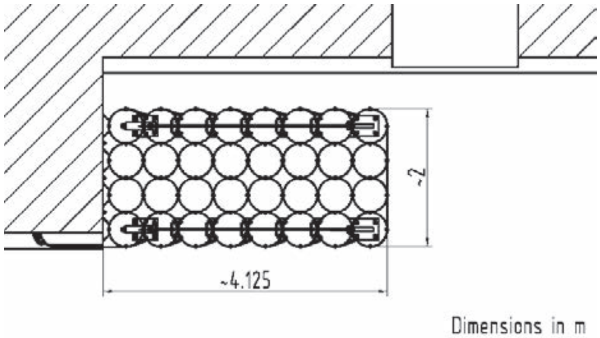
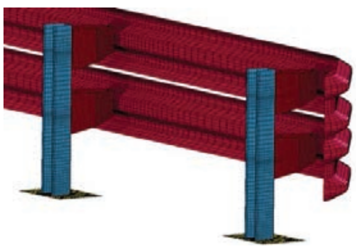
b) 

Fig. 6 (a) Crash cushion geometrical model; (b) Placement of the crash cushion.

The numerical models of the H2-type steel safe-ty railing (Fig. 7a) and the crash cushion (Fig. 7b) were made with the LS-DYNA software package. They were adapted for the needs of FEM analysis with shell finite-element meshing, except for M10, M16 and M18 bolt connections and the steel rope, which were implemented as line elements.

All the sheet metal parts of both safety barriers are made of S 235 structural steel and are modelled using the plastic–kinematic material model (Kunc (2014)).

a) 

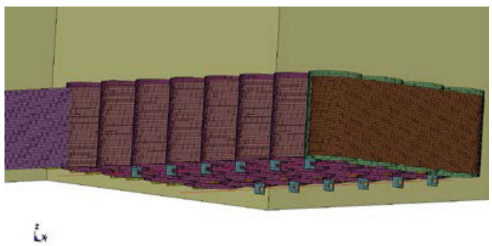
b) 

Fig. 7 (a) SSR numerical model; (b) Crash cushion numerical model.

4.3. Boundary and initial conditions

The initial conditions for each simulated collision of each vehicle into each safety barrier were determined by simulations of driving dynamics immediately prior to the collision. The simulations were performed using PC-Crash software under the assumption that prior to changing direction the vehicles drive with constant velocity and collide into the obstacle without braking. Two different trajectories of approaching a straight tunnel emergency stop area and three different trajectories of approaching a tunnel emergency stop area in a curve were modelled for each of the two vehicles. The trajectories are depicted in Fig. 8 and denoted as follows: driving from the main lane into a straight emergency stop area (1), driving from the overtaking lane into a straight emergency stop area (2), driving from the main lane into a curved emergency stop area (3), driving from the overtaking lane into a curved emergency stop area (4) and an abrupt right turn from the main lane into a curved emergency stop area (5).

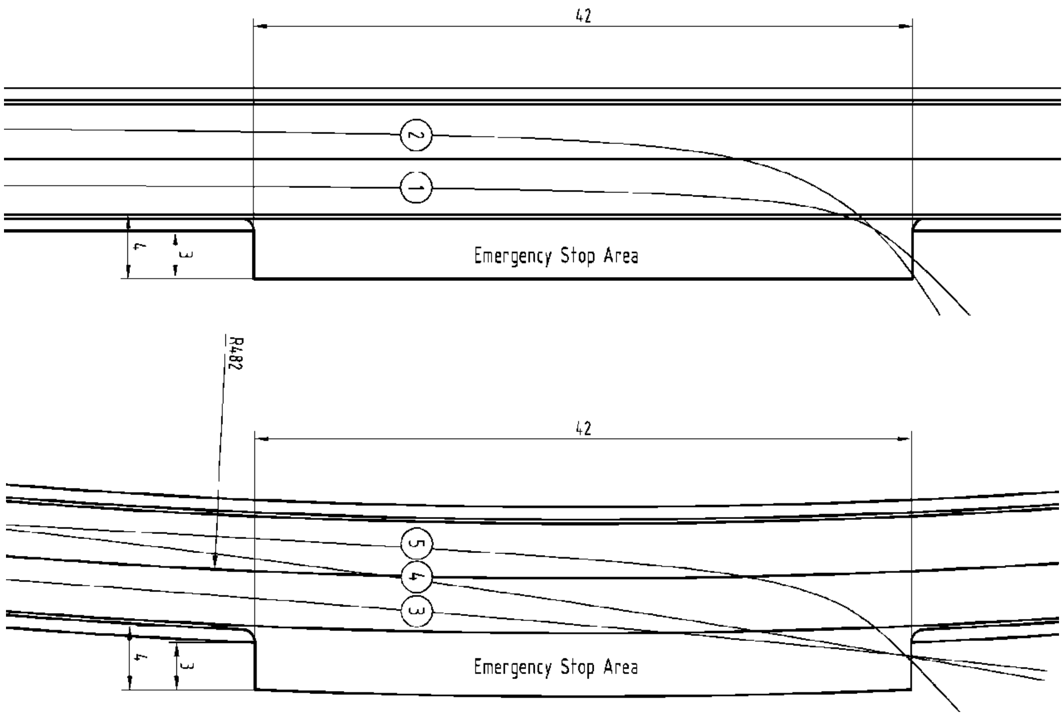
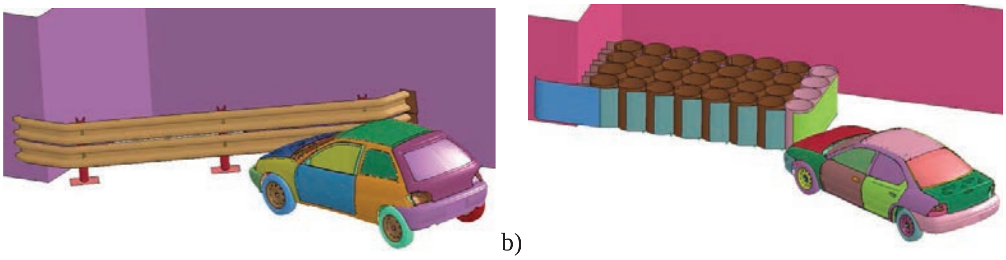


Fig. 8. Trajectories of a vehicle approaching the tunnel emergency stop area on a curved road section (bellow) and on a straight road section (above).

The following kinematic values on the location of the vehicle collision into the safety barrier were calculated for each simulation: vehicle centre of gravity location, vehicle rotation around its vertical axis, vehicle heading, vehicle translational and angular velocity.

The numerical simulation also took into account the gravity and structural non-linearity. The contacts between individual parts contain all the surfaces considering the surface element thickness and inter-surface friction. The static friction coefficient of 0.2 and the dynamic friction coefficient of 0.15 were used in the simulation (Fig. 9).



a) b)

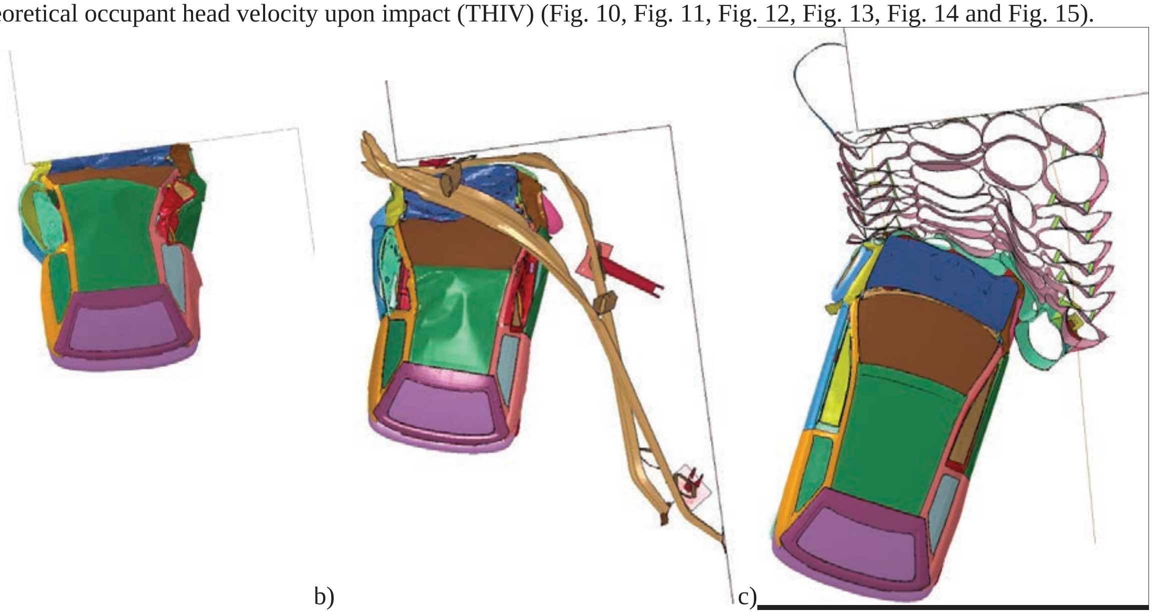
Fig. 9 (a) Numerical model of TB 11 collision into SSR; (b) Numerical model of TB 21 collision into the crash cushion.

4.4. Dynamical analysis

The dynamical analyses of the TB 11 (Suzuki Swift passenger car) and the TB 21 (Dodge Neon Passenger Car) test cases into the SSR and into the crash cushion were performed with Ansys LS-DYNA software package. Geometrical non-linearity (large displacements and rotations) and structural non-linearity (contacts) have been taken into account in simulations. The simulation time steps were determined based on the resonate frequencies of the test vehicle and safety barrier models. The simulation time was 0.4 seconds long, with results write-out every 0.0005 s.

5. Analysis results

The suitability estimation of the measures for protection of the SOS-niche head wall was performed based on the results of the numerical simulations of real collision of TB 11- and TB 21-type test vehicles by comparison analysis of time series and maximal values of acceleration (ASI), post impact occupant head deceleration (PHD) and theoretical occupant head velocity upon impact (THIV) (Fig. 10, Fig. 11, Fig. 12, Fig. 13, Fig. 14 and Fig. 15).



a) b) c)

Fig. 10. TB 11 vehicle 0.4 s after collision into a): unprotected wall, b): safety railing, c): crash cushion (trajectory 4) – driving from the overtaking lane into a curved emergency stop area.

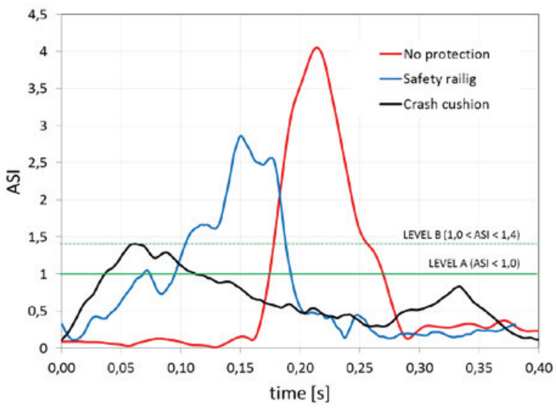


Fig. 11. ASI time series for TB 11, trajectory 4.

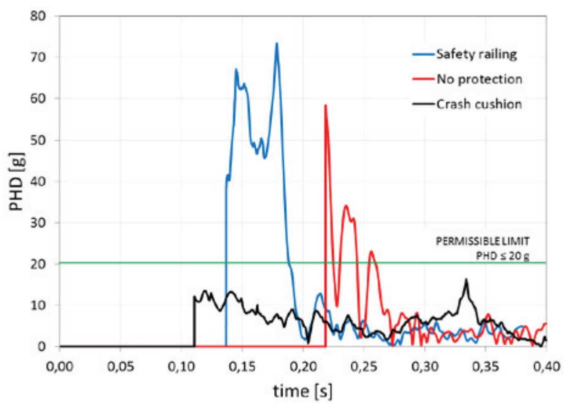
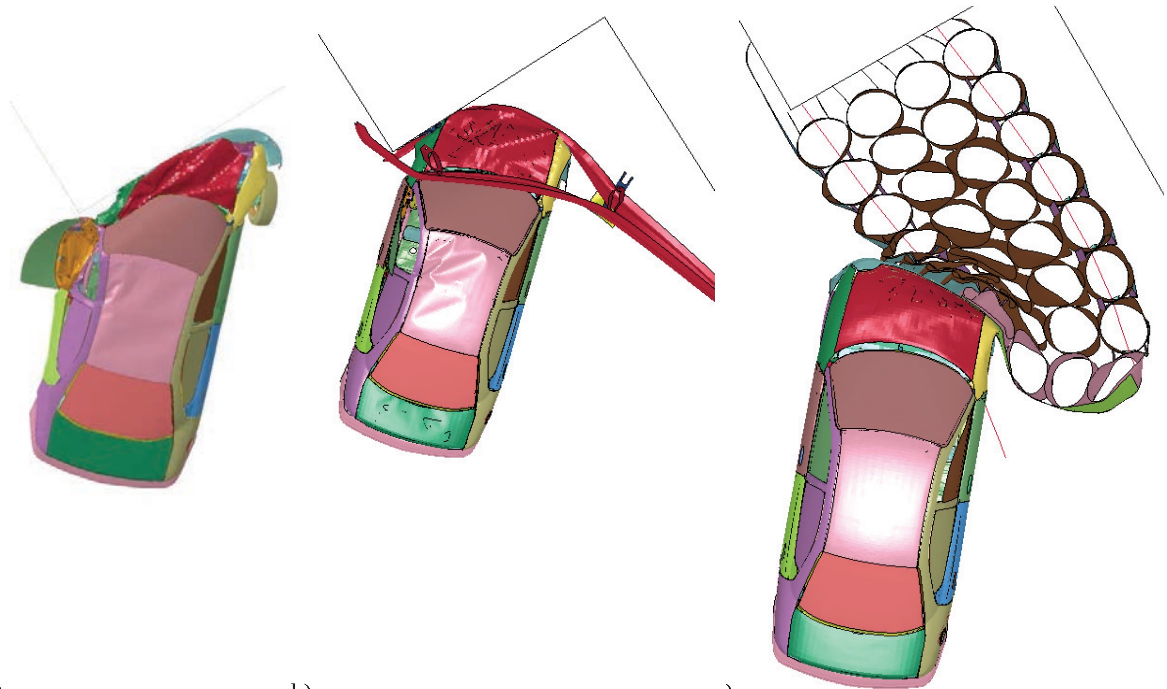


Fig. 12. PHD time series for TB 11, trajectory 4.



a) b) c)

Fig. 13. TB 21 vehicle 0.12 s after collision into a): unprotected wall, b): safety railing, c): crash cushion (trajectory 5) - turning from the fast lane on a road section with a left curve.

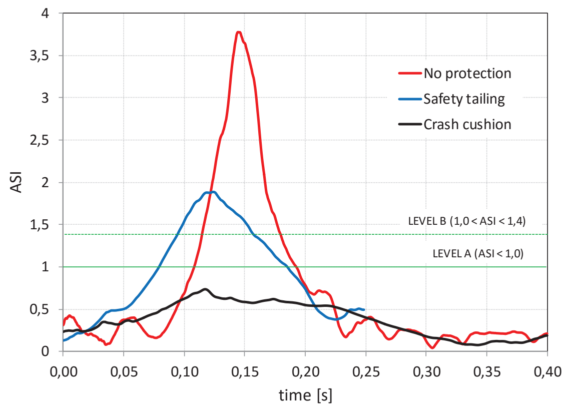


Fig. 14: ASI time series for TB 21, trajectory 5

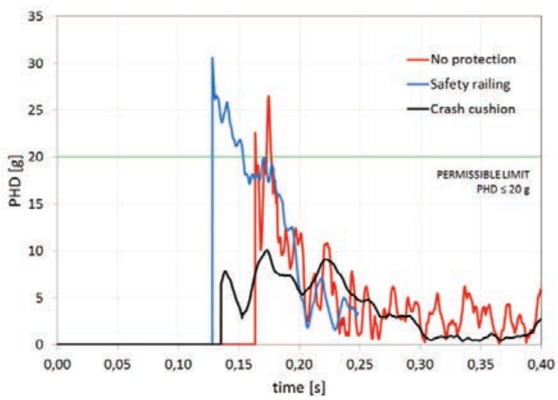


Fig. 15: PHD time series for TB 21, trajectory 5

The comparison of the results of the simulations of the impact of the vehicle into tunnel SOS-niche safety barriers and the impact into an un-protected wall shows an approximately 140% decrease in ASI values for the H2-type steel safety railing and an approximately 240% decrease in ASI values for the VECU-STOP crash cushion (Table 1).

The steel safety railing, compared to the crash cushion, manifests higher maximal ASI values and also larger scatter in the results. The crash cushion, however, manifests larger THIV values. None of the tested protective measures fulfils the standard test criterion for the TB 11 test (900 kg passenger car at 100 km/h). The average ASI values are about 7% above the standard limits for the crash cushion and about 90% above the standard limits for the steel safety railing.

In the TB 21 test all the average values (ASI, THIV and PHD) of the VECU-STOP crash cushion are below the standard limits. The VECU-STOP crash cushion fulfils the strictest A-level, while the elongated SSR implementation fulfils the B-level. The VECU-STOP crash cushion also fulfils the A-level protection criterion in all tests with the 1300 kg passenger car at 80 km/h (Table 1), while the average ASI values are only about 1% above the limit in the SSR.

Table 1. Average and maximal values of ASI, THIV and PHD for different test scenarios.

	TB 11			TB 21		
	SSR	crash cushion	unprotected wall	SSR	crash cushion	unprotected wall
ASI [/] level A: (ASI ≤ 1,0) level B: (1.0 ≤ ASI ≤ 1.4)	**2.67** **max 3.01**	**1.52** **max 1.66**	**3.67** **max 4.05**	**1.47** **max 1.92**	0.70[1] max 0.79	**3.77** **max 4.12**
THIV [km/h] permissible limit THIV ≤ 44 g	43.20 **max 47.59**	**48.54** **max 50.10**	**55.64** **max 63.67**	42.60 **max 52.33**	36.76 max 40.56	**70.53** **max 74.72**
PHD [g] permissible limit PHD ≤ 20 g	**63.85** **max 118.4**	17.63 max 19.49	**55.53** **max 60.75**	**29.12** **max 32.05**	11.47 max 13.54	**47.53** **max 51.89**

Values in bold denote exceeding the upper permissible limits as per EN-1317. [1] denotes compliance to A-level protection as per EN-1317.

6. Conclusion

The purpose of the research was a comparison analysis of the protection measures of the tunnel SOS-niche head wall by means of either a H2-type steel safety railing or a VECU-STOP type element compound crash cushion. According to the EN 1317 standard numerical simulations of the vehicle collisions into the safety barrier were performed for the TB 11 and the TB 21 test. The simulations were done on the finite-element-models using explicit dynamical analysis.

The initial conditions for each individual collision (vehicle centre of gravity location, vehicle rotation, vehicle direction, velocity and angular velocity) into the SOS-niches and various forms of safety barriers were calculated by simulating the vehicle driving dynamics prior to the collision.

Based on the results of the comparison analyses of the Acceleration Severity Index (ASI), Theoretical Head Impact Velocity (THIV) and the Post-impact Head Deceleration (PHD) values it is obvious that the lowest occupant loads due to impact occur in collision with a VECU-STOP-type crash cushion for the TB 11 (900 kg passenger car at 100 km/h) as well as for the TB 21 (1300 kg passenger car at 80 km/h). The crash cushion is composed from four rows of eight steel-sheet open tubes 500 mm in diameter and 850 mm in height. For the TB 21 test such a crash cushion is fully compliant with the strictest A-level protection according to EN 1317. For the TB 21 test case the ASI-value is about 7% above the recommended standard values.

Acknowledgements

The research was commissioned and partly funded by the Slovenian Motorway Company (DARS, d. d.).

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